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In the Matter of

Amendment of the Commission's Rules with
Regard to Commercial Operations in the 3550
-3650 MHz Band

GN Docket No. 12-354

**ON THE IMPORTANCE OF INCLUSION OF RECEIVER PERFORMANCE DATA IN SAS
TO IMPROVE SPECTRUM EFFICIENCY**

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I. INTRODUCTION AND SUMMARY

Spectrum Sharing and Dynamic Spectrum Access (DSA) have been widely acknowledged as key technologies for enhanced access to the spectrum to meet the ever increasing demand for bandwidth. The opening up of 3.5 GHz for commercial use is a major step in that direction. While it is of immense importance to incessantly explore more opportunities for using the otherwise unused spectrum, the efficient usage of the available spectrum is as critical as finding new spectrum. The PCAST report discussed about evolving new metrics for spectrum efficiency to evaluate the wireless systems of the future. In spectral planning, the guard bands play a very important role in protecting the receivers from harmful adjacent channel interference. Each receiver has different performance and tolerance levels to adjacent channel interference. Contrary to the traditional guard band allocations which were largely generic, guard bands carefully crafted to the customized needs of each receiver not only protects all the receivers against harmful interference but also can potentially boost the spectrum efficiency by several orders of magnitude, especially in futuristic heterogeneous networks which is a proposed architecture for the 3.5 GHz. In this paper we develop on the spectrum efficiency metric discussed in the PCAST report and prove via simulations that channel allocations and guard band insertions (termed as ‘spectrum preclusion’) with the knowledge of spectral performance of receivers can potentially give a huge boost to the spectrum efficiency. Such an informed and inclusive optimization by the SAS will ensure the best possible utilization of the available spectrum. Thus, we emphasize on the critical importance of including receiver performance data in the SAS for spectrum management for the proposed 3.5 GHz.

II. THE NEED FOR RECEIVER PERFORMANCE CHARACTERISTICS

Existing spectrum regulations impose stringent restrictions on transmitters and give a free hand to receiver designs, which largely concentrate on cost optimization with certain standardized performance constraints. The assumption that poor receivers would be downplayed by the market was overrated, since previously receivers were almost never vulnerable to adjacent channel interference.^{1,2} The lack of accountability on receiver tolerance limits, though made their service susceptible to degradation due to interference, this was taken care by carefully allocating static bands for transmitters with strict overlay mask regulations along with guard bands. This framework works so long as network level spectrum efficiency is not a concern. However, the static setup for guard bands can potentially create unwanted overheads, especially in a heterogeneous network since the guard band for every receiver would be that of the poorest performing receiver. Such exclusive spectrum allocation schemes and exclusion zones to protect the receivers from interference inherently leads to poor spectrum efficiency.

The spectrum effectiveness (or efficiency), η is defined as^{3,4}

¹FCC Technological Advisory Council, "Interference Limits Policy: The use of harm claim thresholds to improve the interference tolerance of wireless systems," White Paper Version 1.0, February 2013.

² Commerce Spectrum Management Advisory Committee, "Interim Report of Interference and Dynamic Spectrum Access Sub Committee," 2010.

³ President's Council of Advisors on Science and Technology (PCAST), "Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth," 2012.

⁴ P. Marshall, *Scalability, density, and decision making in cognitive wireless networks*, Cambridge University Press, 2012.

$$\eta = \sum_{n=1}^N \frac{R(n)D(n)}{I^2(n)T(n)S(n)}$$

Equation 1

where $R(n)$ is communication range of user n ; $D(n)$ is data delivered for user n ; $I(n)$ is interference range to which other uses of this spectrum (used by user n) is precluded; $T(n)$ is the time taken to deliver data; $S(n)$ is spectrum precluded - the amount of spectrum not available to other users (in other words, the spectrum consumed by the receiver for its operation); and N is the total number of users for a given band (or block) of spectrum over a geographical region. We see that contrary to the conventional definition of spectrum efficiency, this metric has the units bits/(m-s-Hz).

Poor receiver selectivity results in larger spectrum preclusion (or consumption) $S(n)$, and thus resulting in lower efficiency as seen from Equation 1. The ratio $k(n) = \frac{D(n)}{T(n)}$ (denoted as $k(n)$ for simplicity), dictates the achievable data rate for the receiver. Inclusion of $R(n)$ gives emphasis to those systems which can communicate a longer range and if the co-channel interference tolerance is higher, it results in a lower $I(n)$, thus increasing the spectral reuse and thereby increasing the spectral efficiency.

Upon a close observation, it is seen that the new metric for spectrum efficiency very closely relates to the receiver performance. The interference range depends on the interference tolerance limits of the operating receiver at that point and the spectrum preclusion is directly dependent on the adeptness of the receiver to reject signals from adjacent channels. Thus, it is impossible to circumvent the knowledge of these variables and perform an inclusive optimization for network level spectrum efficiency. These parameters are also required for intelligent channel assignments to protect all receivers from harmful interference based on their characteristics. There perhaps exists sub-optimal solutions which can be driven through opportunistic spectrum access via sensing, but in this case it is impossible to ensure adequate protection for all receivers in the network because of the hidden node problem. Thus, to ensure maximum utilization of the proposed 3.5 GHz band, the SAS should include the receiver performance data and optimize for spectrum efficiency.

It is now evident that receiver characteristics play an important role in spectrum management of the proposed 3.5GHz band. While the immediate policy may protect all receivers, another advantage of making the receiver characteristics commonplace is to encourage a competitive market for better performing receivers by giving the consumer knowledge of a radio's quality before they purchase the device. In the eventuality that spectrum becomes extremely congested, a policy engine could enforce a temporary denial of service for poor performing receivers. The SAS could provide a higher priority to those receivers that are more efficient in their spectrum usage and encouraging inefficient users of the spectrum to upgrade their equipment. Alternatively, the policy may define an elevated noise floor that the receivers have to put up with in order to cope up with the increase in demand for spectrum.

Many such details are being considered by several spectrum regulating agencies across the world.^{5,6}

The infamous LightSquared problem could have been potentially avoided had the manufacturers of commercial GPS systems been encouraged to provide receivers with higher selectivity and better interference rejection. Incorporation of quantifiable metrics on receiver performance and making it available to the consumer market would automatically build a healthy competition to provide good quality receivers. Consumers can make rational decisions if they are provided adequate information about the products they buy. A policy that incorporates notifications to the consumers that poor receivers are liable to be denied service at certain times will change the wireless market dynamics and yet provide manufacturers and consumers a great deal of freedom in their design and purchasing decisions.

III. AN EXAMPLE STUDY

We now substantiate our claim by carrying out a small example simulation study to allocate spectrum resources for a network of 8 nodes while maximizing the spectrum efficiency under some constraints. In this we compare the spectrum efficiency obtained in two cases:

1. Receiver performance data (for all receivers) is included in SAS and is used for maximizing spectrum efficiency during resource allocation
2. Receiver performance data (for any receiver) is not included in SAS and hence has not been accounted during resource allocation.

In this paper, we relax the spectrum efficiency metric, by treating the ratio of range of communication and interference as a constant, i.e., $c = \frac{R(n)}{I^2(n)} \forall n$, since we principally emphasize the importance of receiver spectral performance. This approximation amounts to the consideration of the network as a single cell of fixed geographic area without any frequency reuse.

Thus, the spectrum efficiency metric reduces as, $\eta = c \sum_{n=1}^N \frac{k(n)}{S(n)}$, where $k(n) = \frac{D(n)}{T(n)}$ denotes the data rate. Thus, the variable for optimization is the spectrum consumed $S(n)$ and the objective function is the spectrum efficiency metric, $c \sum_{n=1}^N \frac{k(n)}{S(n)}$, which needs to be maximized by choosing optimal values of $S(n)$ for each receiver (Note that different values of $S(n)$ result in different values of $k(n)$, thus making the optimization problem very tough). Different receivers will consume different amounts of spectrum to provide the same data rate, even with the same channel and modulation schemes. This depends on the RF front end nonlinearity which should be captured in the receiver performance characteristics. This spectral performance of the receiver is what needs to be included in the SAS with a suitable policy language. Example curves for the variation of data rates with spectrum consumption is shown for illustrative purposes in Figure 1.

⁵ European Communications Committee, "The Impact of Receiver Standards on Spectrum Management," Report 127, October 2008

⁶ European Communications Office, "The Impact of Receiver Parameters on Spectrum Management Regulations: A Pilot Study," Report 02, June 2010

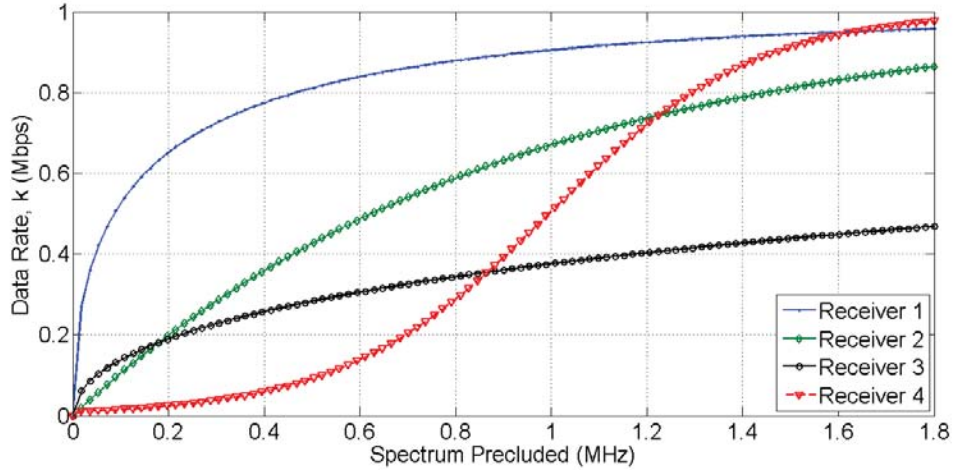


Figure 1. Illustrative curves of spectrum consumed (spectrum precluded) by receivers for a given data rate

In this simulation study, we generate 8 such curves for receiver spectral performance relating to the achievable data rates and use them for numerical optimization to compare it in terms of spectrum efficiency with the case where this data is unavailable to the SAS. We assume a total bandwidth, $B = 5$ MHz to be shared among 8 receivers in the network. Spectrum is allotted in blocks of 180 kHz (similar to LTE physical resource blocks) and the maximum spectrum that can be allocated to a single user is set as, 1.8 MHz (10 blocks). We assume identical channel conditions for all users, which obviates the necessity for any feedback.

For case 1, where receiver performance curves are known to SAS, we enforce a minimum rate constraint, k_0 for each of the 8 users. Minimum rate constraint indirectly specifies that a minimum amount of spectrum should be allotted to each user. We vary this minimum rate constraint starting from 0 kbps, in steps of 100 kbps until 300 kbps (this is the max achievable under the given receiver characteristics of the problem) and evaluate the spectrum efficiency achieved. The achievable spectrum efficiency is shown in Figure 2. All 8 nodes are guaranteed a minimum rate of k_0 .

For case 2, when the spectral profiles of the receivers are unknown, no optimization can be performed in the framework of this problem since the relationship between $S(n)$ and $k(n)$ is unknown to the SAS. Thus, one of the best strategies is to allot equal resources to all users, since we assume identical channel conditions. Thus, equal spectrum is allocated to each user, but the spectrum efficiency varies with the amount of spectrum allocated. Starting from 180 kHz per user until 625 kHz per user (which is the maximum for a bandwidth of 5 MHz and 8 users), we evaluate the spectrum efficiency for each case using the actual data rates achieved for the given spectrum allocated (or consumed by the receivers). The resulting spectrum efficiency and the number of users meeting a set minimum rate constraint are shown in Figure 3.

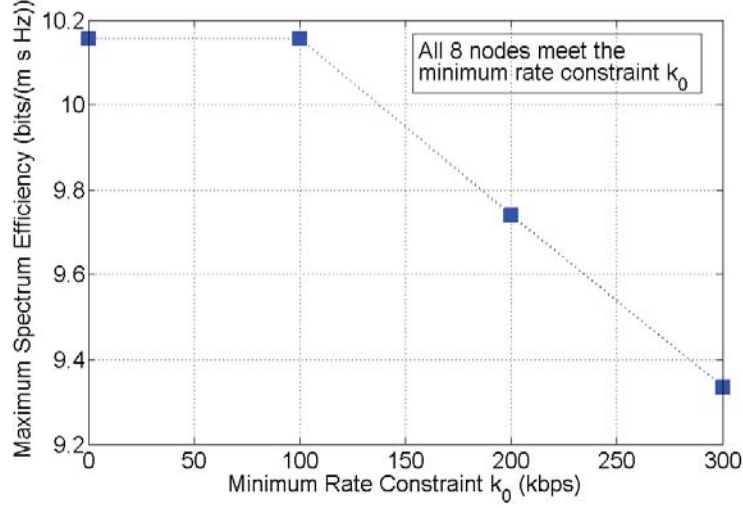


Figure 2. Maximum Achievable Efficiency for the Simulation Setup (with the knowledge of Receiver Spectral Profile)

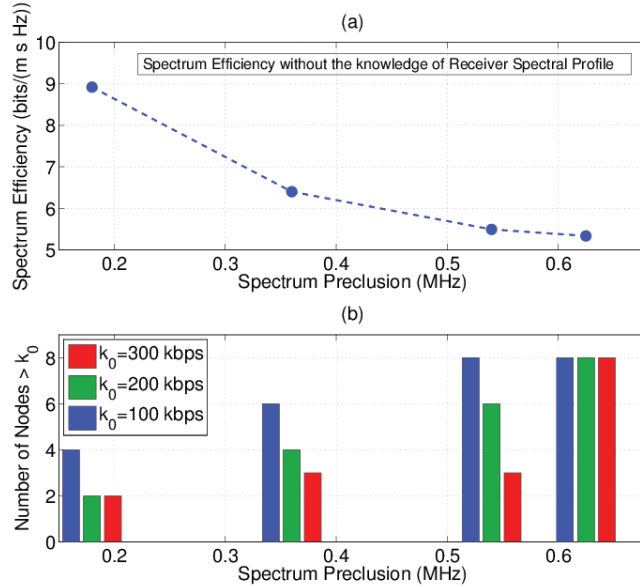


Figure 3. (a) Spectrum Efficiency for given spectrum preclusion (all nodes get equal spectrum) (b) Number of nodes meeting the specified minimum rate constraint, k_0

As seen from the figures, the highest efficiency achieved in case 2 when SAS does not know the receiver performance characteristics is lower than the lowest efficiency achieved in case 1 when SAS knows receiver performance and used for resource allocation. Also, the number of users satisfying a minimum rate is very low in case 2 when receiver performance is unknown, while all the nodes satisfy the minimum rate constraint in case 1 when receiver performance is accounted. If the minimum rates are to be ensured for every user (by providing adequate static guard bands) without the knowledge of receiver performance, the resulting spectrum efficiency is very low. If the receiver performance of all (or at least some) nodes are known, then the SAS can intelligently decide the resource allocation to maximize spectrum utilization by allocating only the required amount of guard bands for each receiver, instead of

wasting spectrum by being over conservative in allocating guard bands or killing the aggregate data rates by reducing guard bands – the SAS only can make guesses. We note that in this simulation study, frequency and time aspects are ignored, with the inclusion of those dimensions, the resulting difference in efficiency between the two cases would only be larger.

IV. CONCLUSION

In this paper, we have emphasized the importance of including receiver performance data in SAS and using it for optimization during resource allocation for the proposed 3.5 GHz band. We have shown that such a framework can boost effective spectrum utilization, thereby reducing spectrum wastage. We draw the attention of the commission to the potential benefits of such a holistic spectrum management scheme and the long lasting benefits that it brings with it.